LESSON 30 – DOPPLER SHIFTS AND RANGE RATE
(Application Exercise 4 due.)
So far, we've seen how the Doppler effect works and how it is affected by pulsing a signal. Now we'll see how Pulse-Doppler radars use the frequency information.

Reading:
Stimson **Ch. 18, 21**, Ch. 25
Problems/Questions:
Finish Application Exercise 4, Work on Problem Set 4
Objectives:
- 30-1 Understand the purpose of Doppler filters and how they affect pulsed-Doppler radar performance.
- 30-2 Understand what is meant by dynamic range.
- 30-3 Know the two methods used to measure range rate.
- 30-4 Understand what Doppler ambiguity is.
- 30-5 Understand the methods used to resolve Doppler ambiguities.
- 30-6 Understand the advantages and disadvantages of low, medium and high PRFs.

Last Time: Computer Application: understanding how changing pulse width, carrier frequency, pulse repetition frequency, and number of pulses affects the shape of the spectrum.

Today: Sensing Doppler frequencies
- Implementation
- PRF Considerations
- Doppler Ambiguities

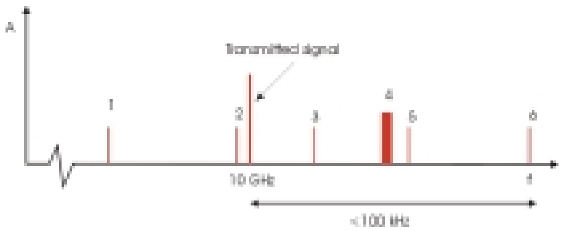
From the computer application, what did you learn?

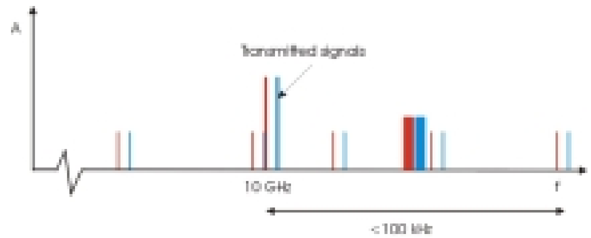
As the number of pulses increases, what happened to the width of the main lobe? What are the units of this width? (Note that this is NOT the antenna beam width we discussed earlier.)
Show pulscale.avi

As the prf went up, what happened to the number of spikes in the main lobe?
Show prfscale.avi

As the pulsewidth went up, what happened to the width of the main lobe?
Show pw.avi

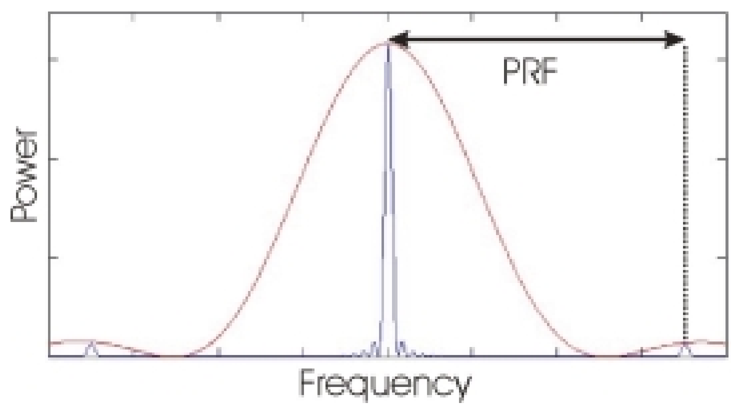
Several lessons ago, I asked a key question: how many frequencies do we want to transmit? I showed the following figures to illustrate that the obvious answer was *one*. Transmitting more than one frequency leads to receiving more than one frequency. Since the difference between the transmitted and received frequency is what tells us the speed of the target, and since we don't know exactly what that frequency difference is, we get ambiguous Doppler shifts when we transmit more than one frequency.





How can you avoid Doppler ambiguities altogether? *Transmit only one significant frequency!*

The word *significant* is critical, as we've seen that with any non-infinite signal, we must transmit more than one frequency. How can we only transmit one significant frequency? Your previous work in the application lesson should come in handy here: What if we transmit a large number of pulses at a high enough PRF that there is only one spectral line under the main peak of the single-pulse spectrum? Voila, we're transmitting only one frequency.



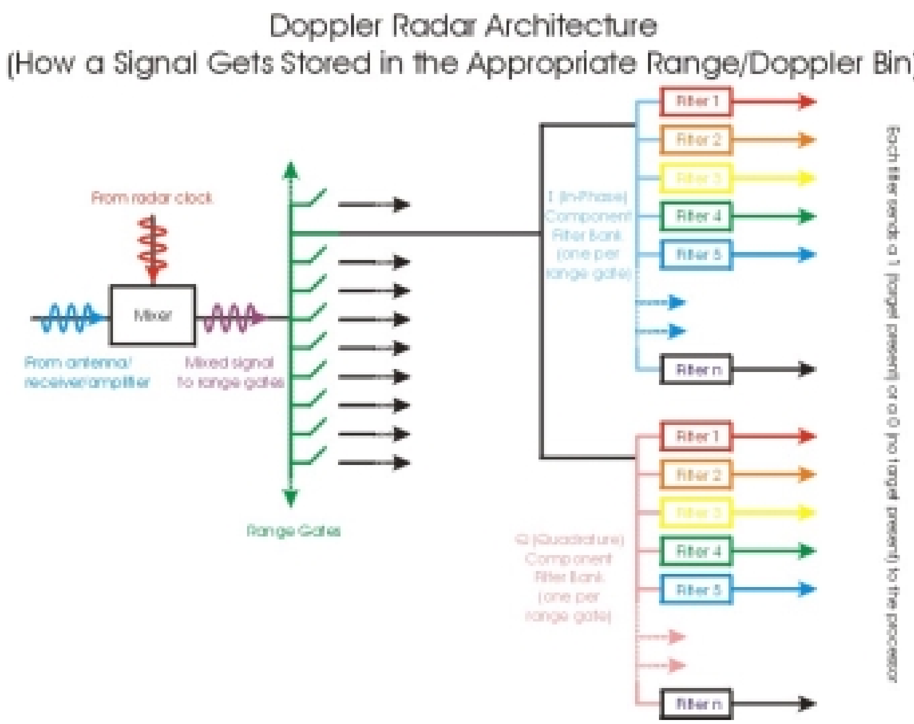
Unfortunately, it's not quite that simple. There are hardware parameters that won't let us achieve this goal. However, we can get a result that's just as good, even though it has a lot of lines in the main spectral lobe. To understand this surprising statement, let's look at how a radar senses range and velocity…

First, as the radar designers, we have to pick some design numbers. Notably, we'll have to decide just how far we will ever need to look (desired max range) and just how accurately we'll have to know the target's velocity (desired velocity resolution). These numbers will determine how much memory and how fast a processor we'll have to build into our radar's processor. See the following table for some example numbers…

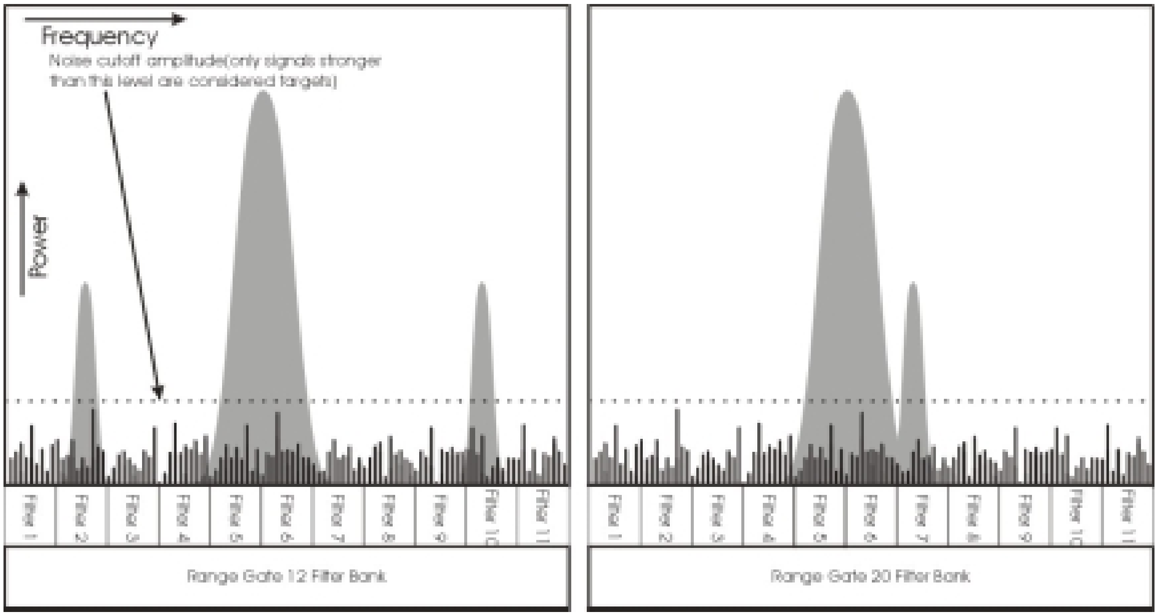
Draw this chart on the side board prior to class

Parameter	**Value**	**Implications**
Pulse Width (τ)	100 ns (= 100ft)	50' best range resolution
PRF (f_r)	105 kHz	Lowest PRF to avoid Doppler ambiguities for expected closures
Desired Max Range	100 NM	Arbitrary pick
Max/Min Expected Closure ($\dot{R}$)	+2000 kts/ -800 kts	Arbitrary pick based on 1000 kt max and 200 kt min speeds; see notes for details
Desired Range Resolution	±½ NM	Arbitrary pick, but requires 200 range gates for our desired max range (100NM/0.5NM)
Desired Velocity resolution	±10 kts	Arbitrary pick, but for our above choices this gives us 350 Hz per Doppler bin $\Rightarrow$ minimum of 300 filters for expected closures (105 kHz/350Hz)

Now that we've come up with the number of range bins and Doppler bins, let's see how the radar actually uses this information.



The radar sends out its signal and then listens for the return. It mixes any returned signal with its reference signal and samples the signal at the local oscillator frequency so that it can see a Doppler shift as a phasor rotation. It sends this signal to the bank of range gates we discussed several lessons ago. Each range gate then has an associated pair of Doppler bins where the signal goes. These bins are essentially a set of narrow band (350 Hz in our example) filters that only allow certain signals to pass. The pair of Doppler bins is required so that both dimensions of the phasor rotation can be sensed, giving an indication of relative velocity and not just relative speed.

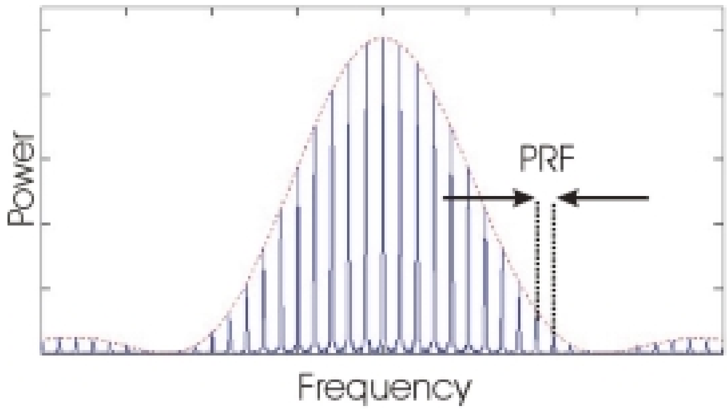


Let's look at a sample return. The left figure represents the spectrum sensed by the radar that passes through range gate number 12. The right figure represents the spectrum sensed by the radar that passes through range gate number 20. Let's say that we'll throw out any return less than a certain value to eliminate noise. This means that the only significant returns are at memory locations (range bin/frequency bin) (12/2), (12/10), and (20/7). There are also very large, broad returns at (12/5), (12/6), and (20/5), (20/6). What do you think they are? Ground clutter. We can "notch" them out by telling the computer to eliminate any returns from Doppler bins */5 and */6. What if we chose a bigger notch? We could do this to avoid fast cars on the Autobahn from triggering the radar, but we might also eliminate the target return in (20/7).

So, how many filters do we need? This is a good review of all previous lessons to make the estimate. We'll spend the rest of the lesson trying to see where the numbers in the chart came from.

We saw earlier that range ambiguities were caused by a high PRF. The closer together the pulses were in time, the less we could tell whether the returns we received were from a specific pulse.

Doppler ambiguities occur from a similar rationale. In order to know PRECISELY what our Doppler shift is, we must only transmit on a single frequency. But as we saw in the computer application, that's not possible without transmitting an infinite wave. The best we can do is to *minimize the width of the lines* of the spectrum of our transmitted signal and to try to *maximize the spacing between the lines*. Ideally, we'd like to have only one spike in our main lobe, the others being sufficiently suppressed by the sinc-squared [$(\sin(x)/x)^2$] envelope of the single pulse. Let's see if this is practical.



How do you go about minimizing line width (LW_{nn})? How about maximizing line spacing? From the application exercise, you should know that lines become narrower the more pulses you put out and the spacing increases with PRF.

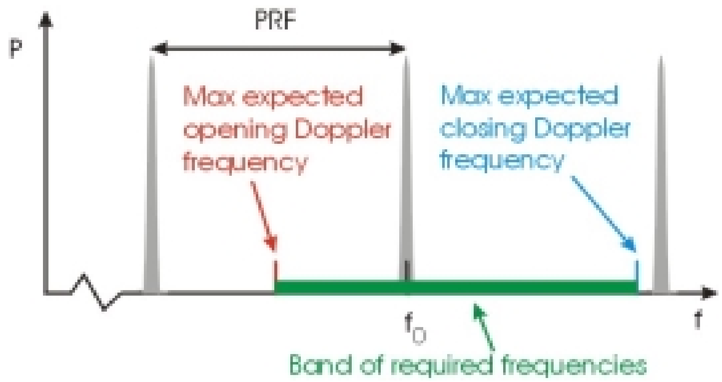
For modern pulse-Doppler radars, the maximum practical PRF is about 200 kHz and the minimum practical pulse width is 100 ns, based on hardware considerations. From last few lectures and the application lesson, you know that the relationship between the null-to-null bandwidth of a pulse and the pulse width is $BW_{nn} = 2/\tau$, so for τ = 100 ns, this gives us BW_{nn} = 20 MHz. The spacing between our significant maxima is equal to the PRF, or 200 kHz, so the best we can do is to have 100 significant spikes in our transmission. This makes our Doppler interpretation quite difficult, since we'd rather transmit on only one frequency!

Is there a way around this? Let's assume the amplitude of the significant spikes near the center of our spectrum are all about the same amplitude, so they must all be considered significant.

What is our max. closing Doppler shift?

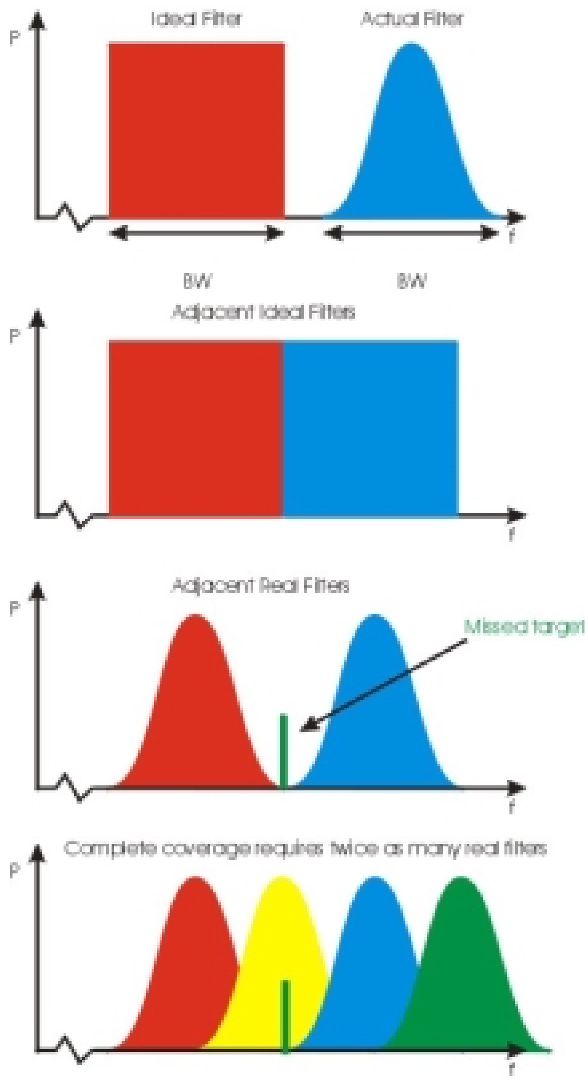
$$\Delta f_d = -\frac{2\dot{R}}{\lambda} = -\frac{2(-2000kts)}{0.03m} * \frac{0.515m/s}{kt} = 68kHz \approx 70kHz$$

What is our maximum opening Doppler shift? If we assume that we can't fly at less than 200 kts and the target is flying away from us at 1000 kts, then the target is flying away from us at 800 kts, giving a Doppler shift of about 30kHz



$$\left(\Delta f_d = -\frac{2\dot{R}}{\lambda} = -\frac{2(800kts)}{0.03m} * \frac{0.515m/s}{kt} = -27kHz \approx -30kHz\right).$$

This means that we need a filter bank for each range gate that covers a range of 100 kHz (+70 to -30) to cover our expected closures. Let's call this number the Doppler filter bank width, or $\Delta f_{d\ max}$. If we make $\Delta f_{d\ max}$ < PRF, then only ONE spike will turn up in the filter bank, no matter how many ambiguities there are inside the main lobe.



Back to our question of how many filters we need for the radar. Let's look at our parameters again. We need to cover 100 kHz worth of Doppler frequencies. 1 kt is approximately equal to 35 Hz, so our 10 knot desired velocity resolution means that we need to cover 350 Hz per filter. This also says that we need about 300 filters to completely cover the expected Doppler spectrum.

But filter response isn't square. It's more like an inverted parabola, so if you put two filters next to each other, you might miss a signal. To fix this, we need twice as many filters, so we're up to 600. But to make sure we know which direction the target's going, we need to sample both dimensions of the phasor (I and Q components), so we double the number of filters again to 1200. We also need to have a complete filter bank for each range gate, so for our desired max. range and desired range resolution of 100kts and ½ kt, respectively, we need 200 range gates, and 200 x 1200 = 240,000 Doppler filters!

Another bit of trivia is that the number of calculations the radar's computer has to do each second is equal to the number of filters times the PRF times 8 (this number comes from Chapter 20 of Stimson – related to forming digital filters and taking their Fourier transform). For our relatively simple radar we've designed, this means we need to be able to do $2.3\text{x}10^{11}$ calculations per second. That's a BUNCH. And that's not even considering beam steering and advanced processing we'll discuss later.

Today, we've seen how some arbitrary choices on things we want our radar to do (max range, min resolvable range, min resolvable velocity) has driven some hardware parameters such as the number of range gates and filters we'll need. We've also seen that some other expected parameters (max and min expected closures) has driven other radar parameters such as the minimum PRF we can use without getting Doppler ambiguities.

Next lesson, we'll see how clutter, returns from the ground, significantly complicate our interpretation of radar returns. If we know about these problems, we can avoid problems for our own radars (or at least be aware of them) and can also devise tactics to make problems for the enemy.